Multi-scale mechanics of the tendon-to-bone attachment

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Introduction

- Joining dissimilar materials is a challenge because of localized stress that develop at interfaces. An effective biologic solution to joining can be seen at the attachment of tendon (a compliant, structural "soft tissue") to bone (a stiff, structural "hard tissue").
- Surgical reattachment of tendon to bone often fails (e.g., the incidence of recurrent tears after rotator cuff repair may be as high as 94%).
- The unique transitional tissue that exists between uninjured tendon and bone is not recreated during healing, even following surgery.
- Tissue engineering strategies hold promise for improving the healing process, but the mechanical structures that exist at the natural tendon-to-bone insertion site and their relative contributions to toughening are not yet characterized.
- We seek to identify the cross-scale toughening mechanisms of the natural tendon-to-bone insertion to drive tissue engineering and repair strategies for improved tendon-to-bone repair.
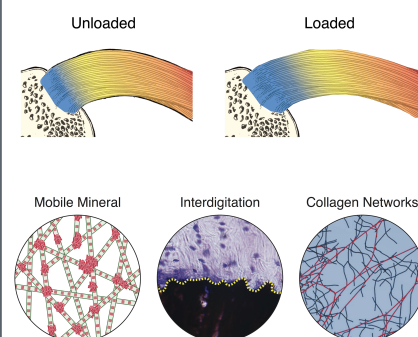
Toughening through disorder

Unloaded   Loaded

Mobile Mineral   Interdigitation   Collagen Networks

Figure 1. (**Top**) The compliant, disordered, energy-absorptive barrier model. In the CDEAB model, deformation localizes to the enthesis (blue) due to its high compliance relative to bone (tan), tendon (yellow), and muscle (red). This high compliance arises in part from disorder in the enthesis. (**Bottom**) The CDEAB model predicts an exceptionally tough enthesis relative to the neighboring tissue because of three known components of disorder: randomly distributed, mobile mineral (red plates); interfacial roughness (yellow dashed line); and disordered fiber arrays (loaded fibers in red, unloaded fibers in blue; cf. Wang et al 2014). Source: Genin and Thomopoulos, *Nature Materials*, 2017

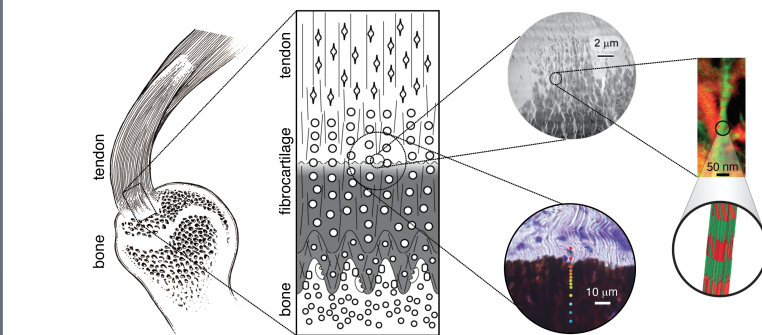## Hierarchical structure of the tendon-to-bone attachment

Figure 2. The hierarchical structure of the tendon-to-bone attachment. At the highest (cm, left) and lowest (nm, right) length scales, the tissue and transitions appear ordered and smooth. At the mesoscale of 100s of nm to 10s of micrometers (images in circles, third from left) stochastic material distributions emerge. [Left : tissue level schematic of tendon-to-bone attachment; second panel from left schematic of transitional tissue, with mineral content indicated by grayscale intensity (modified from Deymier-Black, et al., 2015; third panel from left, top, TEM image of mineral gradient (modified from Schwartz, et al. 2012); third panel from left, bottom, Raman microprobe results of mineral content, with color dots indicating mineral content (red=low, blue=high; modified from Hu et al., 2015); right panel: top TEM EELS image revealing calcium dominated regions (mineral) in red and carbon dominated regions (tropocollagen) in green (Genin and Thomopoulos, 2017).]
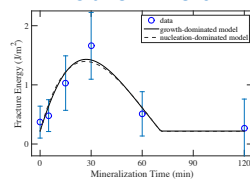
Mobile mineral

Figure 3. Nanofibrous electrospun PLGA laminae were synthesized, then crosslinked and bonded via mobile mineral bridges. Peel test results were predicted by a model combining mineral growth kinetics with fracture energetics, suggesting that fracture resistance increased with mineralization time until mineral mobility was attenuated by steric hindrance, then returned to baseline levels following the rigid percolation threshold.

Interdigitation

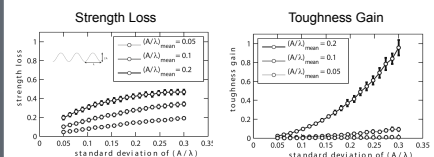Strength Loss   Toughness Gain

Figure 4. The rough, mineralized interface of the native enthesis serves an important role in stress transfer between tendon and bone. The key features are interfacial roughness and interdigital stochasticity. Roughness serves to increase the toughness of the tendon-to-bone insertion site at the expense of its strength. The natural tendon-to-bone attachment presents roughness for which the gain in toughness outweighs the loss in strength.
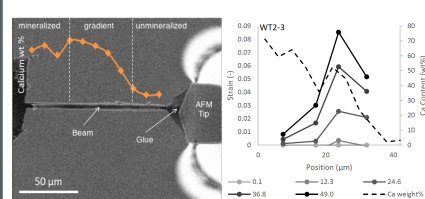
Compliant zone

Figure 4. (**Left**) Tensile micromechanical tests of enthesis beams were performed using an AFM-SEM system. (**Right**) Local strain analysis revealed a compliant zone along the enthesis mineral gradient.

References

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